Applying various methods for assessing soil and sediment redistribution within an intensively cultivated dry valley subcatchment

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Abstract Four independent methods have been employed to evaluate rates of soil and sediment redistribution during a period of intensive agriculture (about 300 years) for a small catchment (area 0.81 km^2) located within the forest zone of the northwestern Russian Plain. These included direct soil survey, radionuclide tracers (^{137}Cs and ^{210}Pb$_{ex}$), and USLE-based modelling. Estimates for cultivated slopes vary from 6.4 to 24.2 t ha^{-1} year^{-1}. Up to 40% of mobilized soil has been redeposited on arable slopes within the catchment. Aggradation of the dry valley bottom has been estimated at 0.3–0.7 m. The intensity of soil and sediment redistribution is low in comparison with forest-steppe and steppe zones of the Russian plain.

Key words deposition; modelling; radionuclide tracers; small catchment; soil erosion

INTRODUCTION

Agricultural development has significantly influenced contemporary geomorphic processes on plains of the temperate climatic belt. Cultivated land expansion resulted in dramatically increased rates of soil erosion, gully formation and other exogenic processes. This general situation, however, significantly varies regionally, depending on local conditions.

The forested area of the Russian Plain, located to the north of Moscow, has been given much less attention in terms of human-induced accelerated soil erosion and sedimentation studies compared to forest-steppe and steppe zones to the south. We have aimed to begin filling this gap by studying soil redistribution within the small dry valley catchment located in the northern part of the Tver region, about 15 km to the southwest of Torzhok city (Fig. 1). Relief is characterized by hills and hilly ridges of glacial origin, with mainly convex slopes. Slope length is, in most cases, insufficient to promote gully formation under local surface runoff conditions. Therefore, sheet and rill erosion, together with mechanical translocation by cultivation, play a major role in soil and sediment redistribution.

CASE STUDY SITE CHARACTERISTICS

The case study area is located in the northwest of the Russian Plain, within the mixed forest zone. Mean annual precipitation is about 600 mm, relatively uniformly distributed within the year. Erosion events can be caused by both intensive snowmelt runoff and occasional

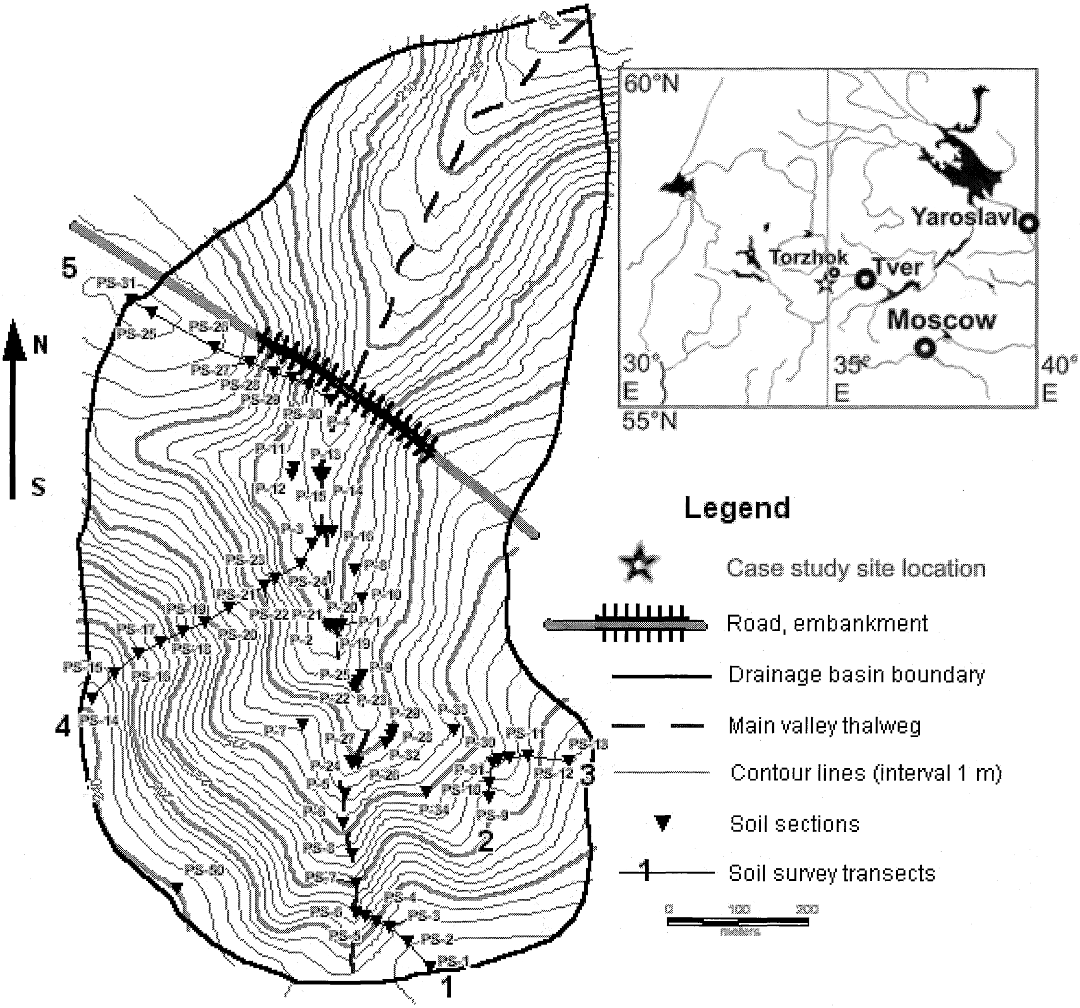

Fig. 1 Map of the northwest of the Russian Plain showing the case study site location and the general study subcatchment scheme with locations of slope transects and soil sections.

summer rainstorms. Rainfall erosivity coefficient of the USLE model is 6.8, estimated for the Torzhok city meteorological station. Soil cover of the region is dominated by podzolic soils formed on glacial or glaciofluvial deposits.

The catchment chosen as a key site for this case study has a drainage area of about 81 ha (Fig. 1). The main valley has a length of about 1.5 km, generally straight long profile (Fig. 2(a)) and average bottom width of 30–40 m. Catchment slopes have different profile shapes, but convex slopes dominate. Slope gradients are moderate, varying from 0.035 to 0.1. A number of slope depressions separate catchment slopes into sections (Fig. 3).

The catchment has been intensively cultivated for at least 300 years. Summer rye, oats, barley and wheat were the main crops before 1917; row crops were not cultivated (Pokrovskiy, 1879). During the Soviet times winter cereals were predominant. After 1991,

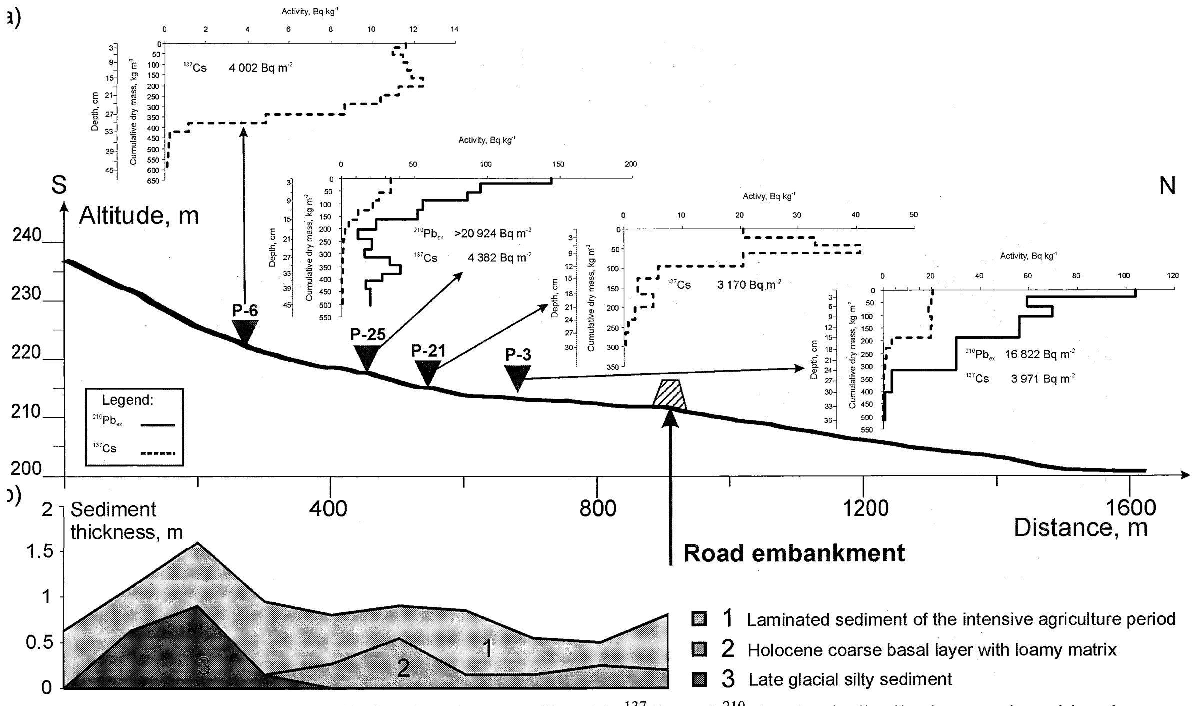

Fig. 2 Studied valley long profile with ^{137}Cs and $^{210}Pb_{ex}$ depth distributions at depositional locations within the bottom (a); and distribution of various sediment layers along part of the valley (b).

arable area slightly decreased and crop rotation changed from cereal-dominated to perennial grass-dominated, which has substantially lowered land vulnerability to water erosion. Today about 80% of the total catchment area is cultivated.

FIELD AND LABORATORY METHODS

The upper part of the study catchment (area about 0.54 km^2) separated by a road embankment, was chosen for the detailed study (Fig. 1). Within this area all major slope types characterizing the entire catchment are represented. The first stage of investigations included topographic and geomorphic mapping. (Figs 1, 3). Soil survey sections along transects within each of the slope types and on the main valley bottom cross sections were excavated and described in detail on the second stage. From some of those, radionuclide tracer soil sampling was carried out. Integral samples were taken from transect 1 (^{137}Cs) and transect 4 (^{137}Cs and $^{210}Pb_{ex}$). Depth-incremental samples were taken from the reference site section PS-31, sections P-3, P-25 (^{137}Cs and $^{210}Pb_{ex}$), P-6 and P-21 (^{137}Cs) (Figs 1, 2(a), 4). Subsequently samples have undergone preparation and counting in the laboratory with counting times not less than 12 h.

Methods employed for estimating soil redistribution rates included soil-morphological method (further—SMM) (Larionov *et al.*, 1973), radionuclide tracers ^{137}Cs (Walling & He, 1999a) and $^{210}Pb_{ex}$ (Walling & He, 1999b), and USLE-based modelling (further—USLE)

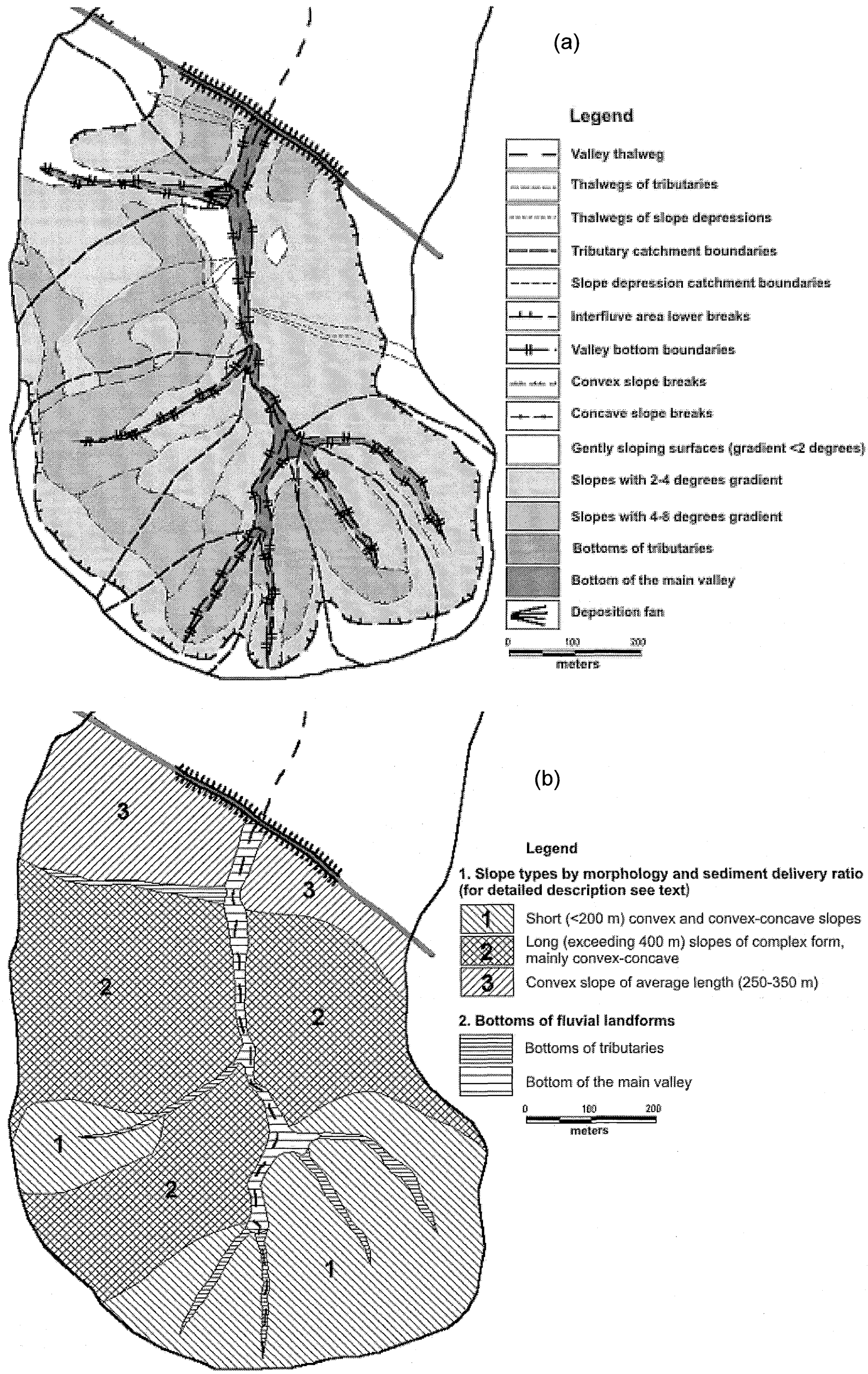

Fig. 3 Slope gradient map (a), and slope morphological types (b) in the study catchment.

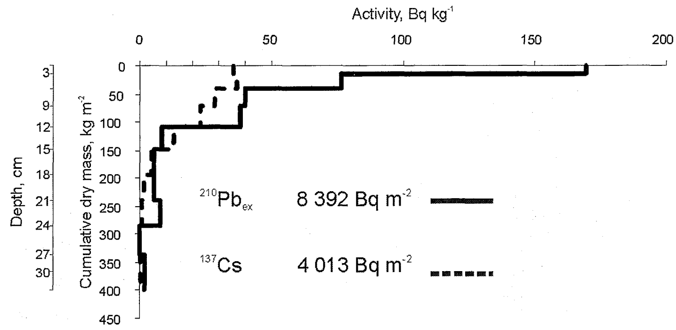

Fig. 4 Depth distribution of ^{137}Cs and $^{210}Pb_{ex}$ in soil at the reference site (section PS-31).

(Larionov *et al.*, 1998; Krasnov *et al.*, 2001). In addition, the total thickness of the valley bottom sediment layer associated with a period of intensive agriculture has been determined (Fig. 2(b)) from abundant charcoal pieces commonly found at its base; the charcoal originates from forest burning during arable land clearing.

RESULTS AND DISCUSSION

Radionuclide tracers reference inventories

Depth distribution profiles of both ^{137}Cs and $^{210}Pb_{ex}$ in soil (Fig. 4) at the reference site (section PS-31, Fig. 1) together with detailed description of soil structure led us to conclude that this site has not been cultivated since at least 1954. Obtained values of the ^{137}Cs and $^{210}Pb_{ex}$ inventories can therefore be used as characteristic for a baseline fallout input in soil redistribution calibration models. About 93% of the ^{137}Cs inventory is found within the upper 15 cm of the section (Fig. 4). Profile shape differs from exponential in the upper part and is characteristic for territories with significant Chernobyl fallout. Modelling of the isotope vertical migration and diffusion (He & Walling, 1997) allowed us to determine its amount as being about 20% of the total inventory. For $^{210}Pb_{ex}$ about 84% of the total inventory is contained within the upper 12 cm of soil. As $^{210}Pb_{ex}$ fallout can be treated as a constant process, annual flux of the isotope from the atmosphere can be calculated from the reference inventory and radioactive decay constant. The value obtained is 260.9 Bq m^{-2} year^{-1}, which is in agreement with direct observations of $^{210}Pb_{ex}$ atmospheric flux (Walling & He, 1999b).

Soil redistribution on the catchment slopes

Three main slope types have been distinguished according to profile shapes, length and slope break locations (Fig. 3(b)), basing on the morphological map of the studied part of the catchment (Fig. 3(a)). These included: (a) short (<200 m) mainly convex or convex-concave slopes (further referred to as Type I slopes); (b) long (≥400 m) slopes of complex form with slope breaks and terrace-like surfaces, but generally convex-concave (Type II); (c) intermediate length (250–350 m) convex slopes (Type III). All three types were characterized by soil survey transects along flow lines (Figs 1, 5, 6, 7).

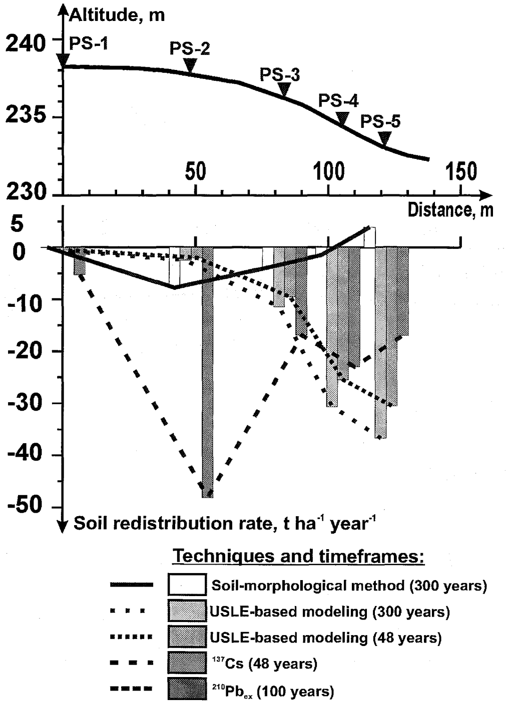

Fig. 5 Slope long profile along transect 1 and soil redistribution rates estimated by different methods.

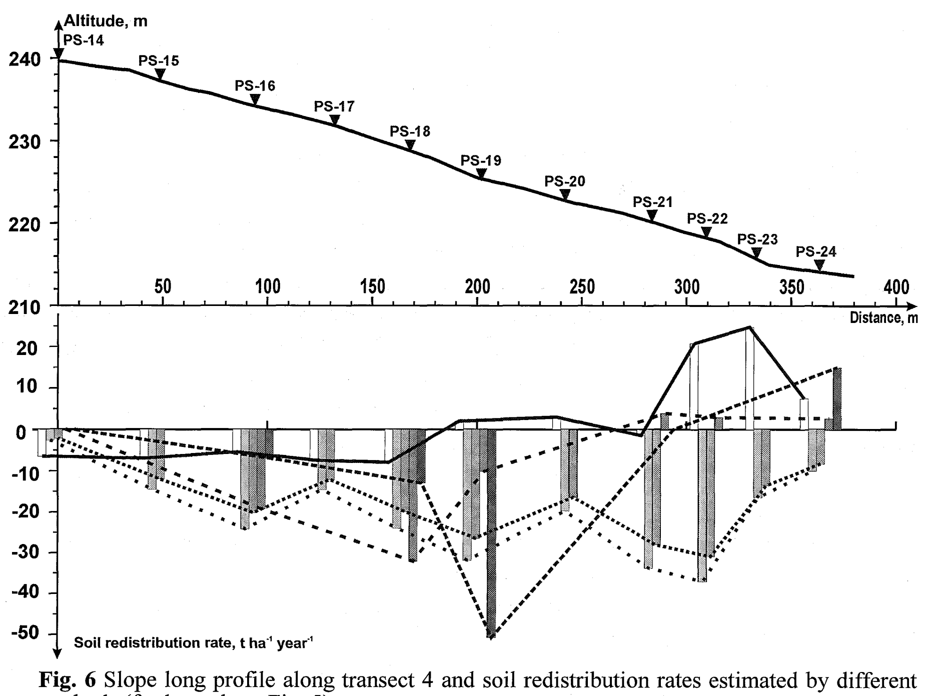

Fig. 6 Slope long profile along transect 4 and soil redistribution rates estimated by different methods (for legend see Fig. 5).

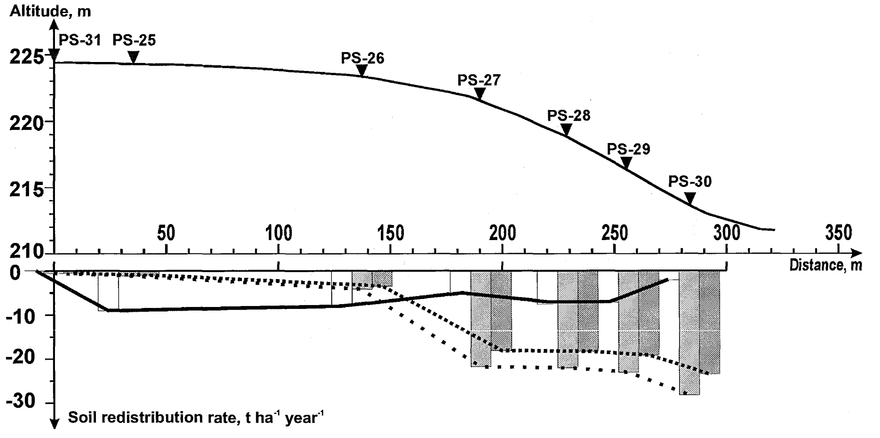

Fig. 7 Slope long profile along transect 5 and soil redistribution rates estimated by different methods (for legend see Fig. 5).

Slopes of Type I are located in the upper part of the studied subcatchment (Fig. 3(b)). These slopes can in turn be subdivided into three subtypes. Shortest (<100 m) convex diverging slopes are located on divides between the main valley and its tributaries. Convex slopes with a flat upper interfluve zone and length of 100 to 200 m characterize the main valley sides. The rest is represented by convex-concave slopes. To characterize all three subtypes, three soil transects were surveyed (Fig. 1, transects 1–3). Data obtained were averaged to characterize all Type I slopes. For transect 1 SMM, USLE and ^{137}Cs methods have been used for soil redistribution rate evaluation (Fig. 5). The first two methods yielded relatively similar values of average soil redistribution rates for the entire cultivation period (6.8 t ha^{-1} $year^{-1}$ from SMM and 9.4 t ha^{-1} $year^{-1}$ from USLE). For the 48 year period of ^{137}Cs presence in the environment (since 1954), this tracer gives a value of 22.6 t ha^{-1} $year^{-1}$, which is almost three times greater than the value (7.8 t ha^{-1} $year^{-1}$) obtained from modelling.

In general, all three methods employed gave an adequate evaluation of the dominance of erosion on Type I slopes. However, SMM is the only method to detect deposition. Its average rate is estimated to be 3.3 t ha^{-1} $year^{-1}$, but its spatial extent is very limited. Zones of erosion occupy about 75% of the Type I slope area, whereas detectable within-slope redeposition occurs only on 14%. Sediment delivery ratios for these slopes vary from 68 to 100% depending on the slope subtype. The only important sediment sinks are slope toes.

The Type II slopes are mainly found in the middle part of the studied subcatchment (Fig. 3b). These are characterized by a complex profile shape and a very gently sloping gradual transition zone to the main valley bottom. For the Type II slopes, all four methods of soil redistribution assessment described above have been employed (Fig. 6). For the 300-year period SMM estimates an average erosion rate of 6.0 t ha^{-1} $year^{-1}$, whereas USLE estimates 18.5 t ha^{-1} $year^{-1}$. Estimation for the 100-year period by $^{210}Pb_{ex}$ (10.0 t ha^{-1} $year^{-1}$) is essentially close to that from SMM. For the 48-year period, USLE gives an average erosion rate of 15.4 t ha^{-1} $year^{-1}$ and the ^{137}Cs method yields 25.8 t ha^{-1} $year^{-1}$.

Sediment redeposition within the Type II slopes is again adequately reflected only by SMM. Its average rate is estimated as 8.1 t ha^{-1} $year^{-1}$. Area of redeposition zones (9.3 ha or 37.6% of the entire Type II slope area) is substantially smaller than that of erosion zones (15.4 ha or 62.4%). The ^{137}Cs and $^{210}Pb_{ex}$ methods most likely underestimate deposition rates. For sections PS-21, PS-22 and PS-23 (Figs 1, 6) presence of accumulation is only confirmed by high activity of both isotopes below the plough layer (comparable or even exceeding that of the plough layer) and an increase in their concentrations in the topsoil downslope, probably reflecting particle size selectivity. Despite this, good agreement is observed in relative area of erosion- and deposition-dominated zones between radionuclide tracers data and SMM. Sediment delivery ratio estimated from SMM is 19%, highlighting the important role of within-slope sediment sinks for the Type II slopes.

The Type III slopes are located only in the lower part of the studied subcatchment nearby the road embankment (Fig. 3(b)). These are characterized by a relatively long (up to 30% of total slope length) flat interfluve section and simple profile shape below with gradient increasing downward and a sharp boundary between slope toe and valley bottom. For the Type III slopes only SMM and USLE have been applied (Fig. 7). Results obtained are between those for the Type I and Type II slopes. Average erosion rates are 6.4 t ha^{-1} $year^{-1}$ according to SMM and 13.3 (300-year period)—11.0 (48-year period) t ha^{-1} $year^{-1}$ from USLE modelling. Simple morphology determines location of the erosion zone (about 80% of the slope length, except the flat interfluve part) and complete long term sediment delivery to the main valley bottom (ratio 100%).

Deposition in the main valley bottom

The geological structure of the main valley bottom is essentially uniform throughout the studied part of the catchment. Total sediment thickness (including pre-anthropogenic) does not exceed 1.5 m, with mean values of 0.8–1.0 m (Fig. 2(b)). Almost everywhere sediment is underlain by Late Pleistocene glacial boulder clays. The sediment layer associated with a period of intensive agriculture is found throughout the studied part of the main valley bottom. Its recent origin is supported by lateral connections with depositional sheets on adjacent slope toes. Within this layer we have observed a number of secondary erosional boundaries and depositional bodies which confirm repeating episodes of local incision and aggradation. Thickness of this layer varies from 0.3 to 0.7 m, the range of aggradation rates calculated from these data, assuming the 300-year cultivation period, are 1.0–2.5 mm $year^{-1}$.

Additional time marks in the main valley bottom sediment sequence have been acquired by analysis of four depth-incremental soil sections for radionuclide content (Fig. 2(a)). Radionuclide depth profiles obtained show that deposition rates within the main valley bottom vary significantly from point to point and in time. The ^{137}Cs depth profiles suggest that some parts of the main valley bottom were recently cultivated, as in its upper reach (section P-6) and low left bank terrace in the middle reach (section P-3). In addition, local bottom incision and infill episodes (sections P-21, P-25) influenced radionuclide content making estimations of average aggradation rates problematic (Figs 1, 2(a)). Nevertheless, approximate values of 1.0 mm $year^{-1}$ (^{137}Cs, 48-year period) and 1.6 mm $year^{-1}$ ($^{210}Pb_{ex}$, 100-year period) have been obtained.

General characteristics of sediment redistribution within the study subcatchment

Results of soil and sediment redistribution investigations by different methods for the studied part of the small valley catchment are summarized in Table 1. Average soil erosion rates on

Table 1 Summary of extrapolations of soil and sediment redistribution characteristics obtained from different methods for the entire studied subcatchment area.

Method	Soil-morphological		USLE-based model		^{137}Cs*	^{210}Pb$_{ex}$†
Period (year)	300	48‡	300	48	48	100
Erosion (t ha^{-1} year^{-1})	6.4		14.5	12.0	24.2	10.0
Area of erosion zones (ha/%§)	35.2/65.3		–	–	42.2/78.3	31.9/59.1
Erosion over the period (t)	67350.0	10776.0	220770.3	29323.4	49019.5	31914.0
Within-slope redeposition (t ha^{-1} year^{-1})	6.7		–	–	6.4	5.1
Area of within-slope redeposition zones (ha/%)	13.0/24.1		–	–	8.6/16.0	16.1/29.8
Within-slope redeposition over the period (t)	26190.0	4190.4	–	–	2640.0	8211.0
Sediment yield from slopes over the period (t)	41160.0	6585.6	220770.3	29323.4	46379.5	23703.0
Sediment delivery ratio (t)	61		–	–	95	74.3
Deposition in the valley bottom (t ha^{-1} year^{-1})	21.2**	15.7§	21.2**	15.7††		22.5‡‡
Area of the valley bottom (ha/%)	3.1/5.8					
Deposition in the valley bottom over the period (t)	19690.0**	2332.5§	19690.0**	2332.5††		6975‡‡

*From slope transects 1 and 4 only.
†From slope transect 4 only.
‡Extrapolated from longer-term estimates assuming similar average soil redistribution rates.
§Percentage of the studied subcatchment (total area of approximately 54 ha).
**Estimated from sediment section descriptions.
††Estimated from ^{137}Cs data.
‡‡Estimated from ^{210}Pb$_{ex}$ data.

the catchment slopes are moderate—estimations from different techniques vary from 6.4 to 24.2 t ha^{-1} year^{-1}. In most cases two zones of intensive erosion can be distinguished: upper slope convexity and the lower third of the slope. The former can be attributed to significant contribution of soil translocation by tillage, whereas the latter is associated with water erosion. It is believed that erosion rates have been decreasing since 1991, when a shift to less erosion-prone crop rotations dominated by perennial grasses began. This decrease is confirmed by the USLE calculations, but has no support from ^{137}Cs data because in our case it has overestimated erosion and underestimated deposition rates. Most likely explanations for this problem are: (a) insufficient sampling depth; (b) high spatial variability of the initial fallout has not been adequately statistically assessed; and (c) the calibration model does not account for the influence of extreme erosion events on ^{137}Cs content in soil. The ^{210}Pb$_{ex}$ method is less vulnerable to extremes as its annual fallout can be assumed to be constant (Robbins, 1978).

Within-slope accumulation of sediment is believed to be adequately reflected by SMM only. Deposition zones are most often found at slope toes and along boundaries or transition zones between slope and valley bottom. Additional within-slope sediment sinks exist on longer slopes with complex profile. Those can intercept up to 40% of the material eroded from upslope. The version of the USLE-based model employed is unable to account for within-slope redeposition, therefore its applicability for morphologically complex slopes (Type II) is limited.

Valley bottom aggradation in the studied catchment is much slower than that observed in similar catchments of forest-steppe and steppe zones of the Russian Plain (Golosov, 1998). During the last 48 years, as ^{137}Cs data from depositional locations suggest, the average rate of valley bottom aggradation has significantly decreased. This fact is in agreement with a recent decrease of soil erosion rates on catchment slopes. Local processes of bottom incision and infill are associated with increased erosion and deposition rates, but essentially result in sediment redistribution within the main valley bottom and do not influence the studied catchment sediment budget. In the longer term, as shown by SMM and $^{210}Pb_{ex}$ data, from half to two thirds of mobilized sediment has remained within the catchment, although this value requires further validation. The main results have been the smoothing of geomorphic boundaries, a slight decrease in local topography range and substantial transformation of the soil cover microvariability as various types of degraded, aggraded and degraded-aggraded soils have come into existence.

CONCLUSIONS

Modern rates of soil degradation on the studied catchment slopes (6.4–24.2 t ha^{-1} $year^{-1}$ by different methods) are moderate, but significant in terms of soil degradation as soils in the region are shallow, have low fertility and recover slowly. Sediment delivery from slopes and rates of valley bottom aggradation (1.0–2.5 mm $year^{-1}$) observed are low compared to those reported for similar catchments in forest-steppe and steppe zones of the Russian Plain.

General coincidence of spatial pattern of erosion and deposition zones on the most complex Type II arable slopes determined by soil-morphological and radionuclide tracer methods suggests the main tendency of soil and sediment redistribution has remained similar throughout the period of intensive agriculture. Maximum erosion occurs on upper convexities (associated with tillage translocation) and the steepest middle parts of slopes (associated with water erosion), with maximum deposition occurring at the toe of slopes.

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